Factors Affecting Machinability of Metals

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“Machinability” is not an exact term. It may be defined as the relative ease or difficulty of removing metal in transforming a raw material into a finished product with the desired dimensional requirements at the best cost. Since it is not an absolute material property, machinability means different things to different people. When one states that material A is more machinable than material B they may be referring to,

- Material A having longer tool life compared to B,
- Material A requiring lower cutting forces and power compared to B, or
- Material A providing better surface finish compared to B.

In general high hardness will lead to poor machinability, however many other factors affect machinability. Factors affecting machinability include tool material, feeds, speeds, cutting fluids, rigidity of the tool holding device, and the microstructure, grain size, heat treat condition, chemical composition, fabrication methods, hardness, yield and tensile strength of the work piece.

Among the many different metals available, some are easier to machine than others. Many years ago, a system was developed to rate the relative ease or difficulty of machining various metals. These ratings are called “Machinability Ratings” (MR) and they provide a starting point for understanding the severity of a metalworking operation.

Machinability ratings are used when selecting tool material, feed rates, coolants, cutting oils, and machine speeds for metal cutting and grinding operations. The machinability rating of a metal takes the normal cutting speed, surface finish and tool life attained into consideration. These factors are weighted and combined to arrive at a final machinability rating. The American Iron and Steel Institute (AISI) tested many alloys and compared the normal cutting speed, tool life and surface finish to that obtained when machining AISI 1112 steel. Machinability ratings are “relative” ratings. It is a relative measure of how easily a material can be machined when compared to a standard. That standard is 160 Brinell hardness AISI 1112 cold drawn steel, machined (turned) with a suitable cutting fluid at cutting speed 180 surface feet per minute under normal cutting conditions using high-speed-steel tools. 1112 was assigned a score of 100. Materials with scores above 100 are easier to machine than 1112. Likewise, materials with scores of less than 100 are more difficult to machine. For example, Inconel (a nickel-chrome based superalloy) is very difficult to machine and it has a rating of 9.

These relative ratings are often called “percent machinability”, and represent the relative speed to be used with each given material in order to obtain a given tool life. For example, a material whose rating is 50 should be machined at approximately half the speed used for the material rating 100, if equal tool life is desired for either of them.

The machinability rating of some of the common materials are listed below. These ratings were established for materials with Brinell hardness numbers (BHN) as listed. When a material listed is to be machined and is found to have a BHN different from that shown in the table, a ratio is applied. The ratio of the BHN in the table to the actual BHN of the workpiece is multiplied by the listed machinability rating to provide the MR of the actual workpiece. For example, a 4140 steel at a BHNof 190 is shown on the table to have an MRof 55. Let's assume the 4140 to be machined has an actual BHN of 220. Therefore 190 divided by 220 times 55 equals 48. This means the machinability of the 4140 with a BHN of 220 has an MR of 48.

AISI	Rating, %	Brinell hardness
1008	55	155
1010	55	150
1020	65	148
1030	65	190
1045	50	217
1095	45	210
1112	100	160
1113	135	170
4140	55	190
4340 (100% pearlitic)	45	221
4340 (Spheroidized)	65	206

8620	60	194
Gray Cast Iron	70	190
Ductile Iron	50	200
Hastelloy X	9	197
Inconel X	15	360
304 Stainless	40	160
316 Stainless	35	195
410 Stainless	55	160
416 Stainless	90	200
440C Stainless	35	240
A356 Aluminum	140	-
2024 Aluminum	150	-
6061 Aluminum	190	-

Machinability Ratings of Various Materials

The second approach in machinability rating is in terms of equivalent cutting speed. The cutting speed number is the cutting speed, which causes a given flank wear land in 60 minutes. Such a cutting speed is called economical cutting speed. However, 60 minutes of tool life is no longer considered economical. The economical tool life for minimum machining cost is about 10 minutes or less in turning. Therefore, the corresponding cutting speed is much higher than the tool life of 60 minutes.

The third approach in machinability ratings represents relative cutting speed values where the ratings are given as letters, as shown in Table below for various stainless steels. “A” indicates a high permissible cutting speed and “D” a lower cutting speed.

AISI	**Rating**	**Brinell hardness**
410	C	135-165
416	A	145-185
430	C	145-185
446	C	140-185
302	D	135-185
303	B	130-150
316	D	135-185

Machinability Ratings of Hot-rolled, Annealed Stainless Steels
A: Excellent, B: Good, C: Fair, D: Poor

The fourth approach is the correlation of tool life and the microstructure of the metal. Generally speaking hard constituents in the structure (oxides, carbides, inclusions) result in poor tool life. In addition, the tool life is usually better when the grain size of the metal is larger. The correlation of microstructure of steels and tool life was studied by researchers and average relations of tool life and surface finish to microstructure were reported as “good”, “fair”, and “poor”, as shown for some low and medium carbon steels below.

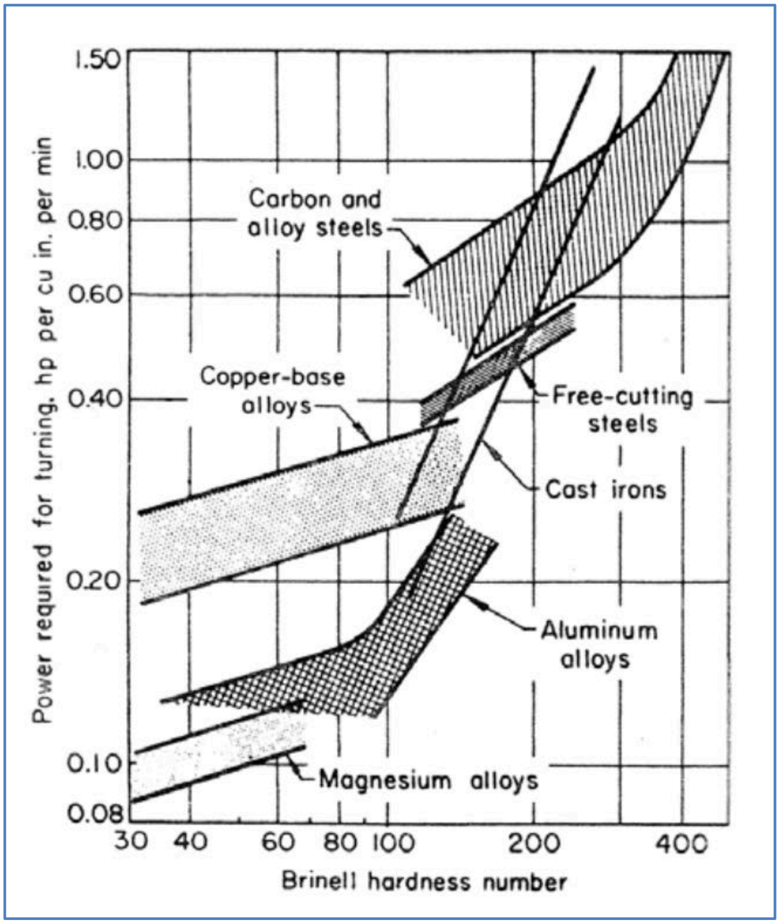
Class of Steel	**Structure**	**Tool life**	**Surface finish**
Low-carbon steels	Cold-drawn, small grain size	Good	Good
	Normalized	Good	Fair
Medium-carbon steels	Pearlitic, moderate grain size	Good	Good
	Pearlitic, small grain size	Fair	Good
	Pearlitic, large grain size	Good	Fair
	Spheroidized	Fair	Poor

Average Relation of Tool Life and Surface Finish to Microstructure of Steels

Another general statement that can be made is that, pure metals tend to adhere to the working surfaces of the cutting tool and give high friction and high tool-wear rates. For example, when pure iron is machined, cutting forces and tool wear rates are almost as high as those experienced when some of the very tough alloy steels are machined.

JUDGING MACHINABILITY

Depending on the application, machinability may be defined in terms of tool wear rate, total power consumption, attainable surface finish or other benchmarks. Machinability not only depends a great deal on the viewpoint of the observer but also on the joint influences of a large number of factors, many of which are quite complex. For example, machinability is certainly closely linked to the physical and mechanical properties of the workpiece. As shown in the figure below, hard, brittle metals being generally more difficult to machine than soft, ductile ones. However, very ductile metals, such as pure copper, stainless steels and some aluminum alloys tend to form long stringy chips, which makes them difficult to machine. Machinability is also strongly dependent on the type and geometry of tool used, the cutting operation, the machine tool, metallurgical structure of the tool and workpiece, the cutting/cooling fluid, and the machinist's skill and experience. It is therefore not possible to describe machinability precisely and that, the term can only have meaning in a loose quantitative sense.



Influence of workpiece hardness on machinability
(ASM Handbook, 8th ed. Vol.3)

The factors affecting machinability along with four common methods used to judge machinability are discussed below:

Tool Life: Tool life may be defined as the period of time that the cutting tool performs efficiently. Many variables such as material to be machined, cutting tool material, cutting tool geometry, machine condition, cutting tool clamping, cutting speed, feed, and depth of cut, make cutting tool life determination very difficult. Metals that can be cut without rapid tool wear are generally thought of as being quite machinable, and vice versa. A workpiece material with many small but hard inclusions may appear to have the same mechanical properties as a less abrasive metal. It may require no greater power consumption during cutting. Yet, the machinability of this material would be lower because of its abrasive properties, which will be responsible for rapid wear on the cutting tool, resulting in higher machining costs.

One problem arising from the use of tool life as a machinability index is its sensitivity to the other machining variables. Of particular importance is the effect of tool material. Machinability ratings based on tool life cannot be compared if a high-speed steel tool is used in one case and a sintered carbide tool in another. The superior life of the carbide tool would cause the machinability of the metal cut with the steel tool to appear unfavorable.

Tool Forces and Power Consumption: The use of tool forces or power consumption as a criterion of machinability comes about for two reasons. First, the concept of machinability as the ease with which a metal is cut implies that a metal through which a tool is easily pushed should have a good machinability rating. Second, the more practical concept of machinability in terms of minimum cost per part machined, relates to forces and power consumption.

When using tool forces as a machinability rating, either the cutting force or the thrust force (feeding force) may be used. The cutting force is the more popular of the two since it is the force that pushes the tool through the workpiece and determines the power consumed. Although machinability ratings could be listed according to the cutting forces under a set of standard machining conditions, the data are usually presented in terms of specific energy (the energy consumed in removing a unit volume of material). Workpiece materials having a high specific energy of metal removal are said to be less machinable than those with a lower specific energy.

The use of net power consumption during machining as an index of the machinability of the workpiece is similar to the use of cutting force. Again, the data are most useful in terms of specific energy. One advantage of using specific energy of metal removal, as an indication of machinability is that it is mainly a property of the workpiece material itself and is quite insensitive to tool material. By contrast, tool life is strongly dependent on tool material.

Surface Finish: The quality of the surface finish left on the workpiece during a cutting operation is sometimes useful in determining the machinability rating of a metal. Some workpieces will not yield a good finish as well as others. The fundamental reason for surface roughness is the formation and sloughing off of parts of the built-up edge on the tool. Soft, ductile materials tend to form a built-up edge rather easily. Stainless steels, and other metals with high strain hardening ability also tend to machine with built-up edges. Materials which machine with high shear zone angles tend to minimize built-up edge effects. These include the aluminum alloys, cold worked steels, free-machining steels, brass and titanium alloys. If surface finish alone were the chosen index of machinability, these latter metals would rate higher than those in the first group.

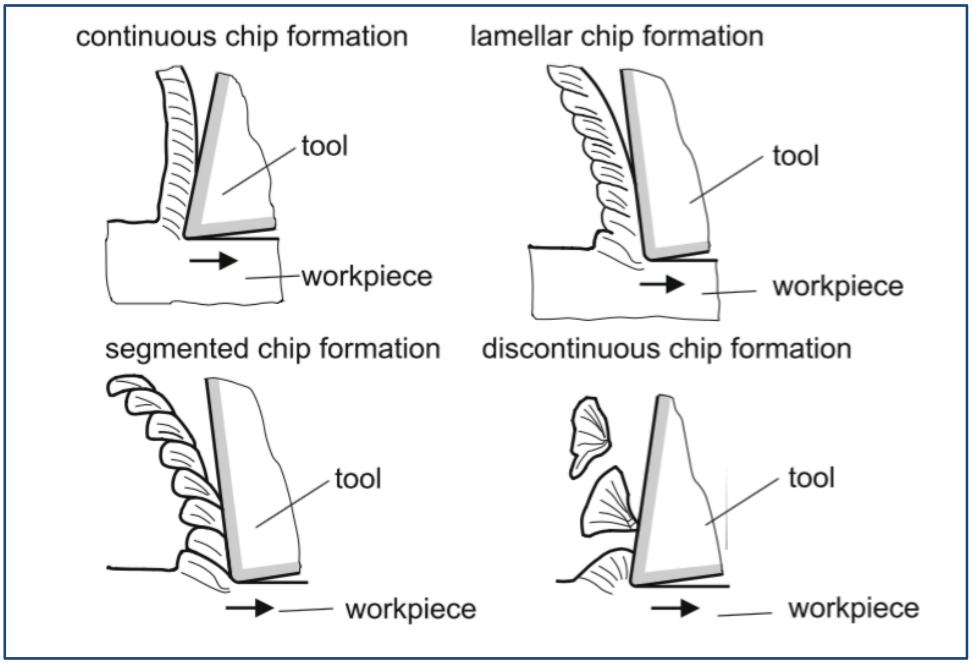
In many cases, surface finish is a meaningless criterion of workpiece machinability. In roughing cuts, for example, no attention to finish is required. In many finishing cuts, the conditions producing the desired dimension on the part will inherently provide a good finish within the engineering specification. Machinability figures based on surface finish measurements do not always agree with figures obtained by force or tool life determinations. Stainless steels would have a low rating by any of these standards, while aluminum alloys would be rated high. Titanium alloys would have a high rating by finish measurements, low by tool life tests, and intermediate by force readings.

Chip Form: There have been machinability ratings based on the type of chip that is formed during the machining operation. The machinability might be judged by the ease of handling and disposing of chips. A material that produces long stringy chips would receive a low rating, as would one that produces fine powdery chips. Materials, which inherently form nicely broken chips would receive top rating. Stringy chips are a menace to the operator and to the finish on the freshly machined surface. However, chip formation is a function of the machine variables as well as the workpiece material, and the ratings obtained by this method could be changed by provision of a suitable chip breaker. Ratings based on the ease of chip disposal are basically qualitative, and not widely used for interpreting machinability. It finds some application in drilling, where good chip formation action is necessary to keep the chips running up the flutes. However, the whipping action of long coils once they are clear of the hole is undesirable.

Chip Formation

Regardless of the tool being used or the metal being cut, the chip forming process occurs by a mechanism called plastic deformation. In cutting and abrasive processes, the cutting edge penetrates into the workpiece material, which is thus plastically deformed and slides off along the rake face of the cutting edge. This is called chip formation. Depending on the deformation behavior of the workpiece material and the cutting conditions, the following mechanisms of chip formation can be distinguished (illustrated in below figures).

- continuous chip formation
- lamellar chip formation
- segmented chip formation
- discontinuous chip formation.



Continuous Chip: In continuous chip formation the chip slides off along the rake face at a constant speed in a stationary flow. Continuous chip formation is promoted by a uniform, fine-grained structure and high ductility of the workpiece material, by high cutting speeds and low friction on the rake face, by positive rake angles and a low undeformed chip thickness. This type chip is a continuous ribbon produced when the flow of metal next to the tool face is not greatly restricted by a built-up edge or friction at the chip tool interface. The continuous ribbon chip is considered ideal for efficient cutting action because it results in better finishes.

Lamellar chip formation is a continuous, periodic chip formation process similar to pure continuous chip formation. However, there are variations in the deformation process that cause more or less significant cleavages or even concentrated shear bands. Lamellar chips occur with highly ductile workpiece materials with an increased strength, especially at high cutting speeds.

Segmented chip formation is the discontinuous formation of a chip with still more or less connected elements, yet with significant variations in the degree of deformation along the flow path. It primarily occurs with negative rake angles, lower cutting speeds and a higher chip thickness.

Continuous Chip with a Built-up Edge (BUE): The metal ahead of the cutting tool is compressed and forms a chip that begins to flow along the chip-tool interface. As a result of the high temperature, the high pressure, and the high frictional resistance against the flow of the chip along the chip-tool interface, small particles of metal begin adhering to the edge of the cutting tool while the chip shears away. As the cutting process continues, more particles adhere to the cutting tool and a larger build-up results, which affects the cutting action. The built-up edge increases in size and becomes unstable. Eventually a point is reached where fragments are tom off. Portions of these fragments that break off can stick to both the tool and the workpiece. Built-up edges only occur if;

- the workpiece material promotes strain-hardening,
- the chip formation is stable and largely stationary,
- there is a stagnant zone in the material flow in front of the cutting edge,
- the temperatures in the chip formation zone are sufficiently low and do not allow for recrystallization. Built-up edges influence the cutting edge geometry. When they move off, they can drag along workpiece particles (adhesive wear). Sometimes strain-hardened parts of the built-up edges are integrated into the newly formed workpiece surface. Therefore, the formation of built-up edges is generally undesirable. However, it does not occur at higher cutting speeds and resulting higher temperatures in the chip formation zone, because there is no strain-hardening if the recrystallization temperature is exceeded during the deformation process.

The build-up and breakdown of the built-up edge occur rapidly during a cutting action and cover the machined surface with a multitude of built-up fragments. These fragments adhere to and score the machined surface, resulting in a poor surface finish.

Discontinuous Chip: Discontinuous chip formation occurs if the ductility of the workpiece material is very low or if predefined slide paths are formed due to inhomogeneities in the material (e. g. if gray cast iron with flake graphite is machined). Parts of the workpiece material are ripped out of the compound material without significant deformation. Discontinuous or segmented chips are produced when brittle metal such as cast iron and hard bronze are cut or when some ductile metals are cut under poor cutting conditions. As more stress is applied to brittle metal by the cutting action, the metal compresses until it reaches a point where rupture occurs and the chip separates from the un-machined portion. This cycle is repeated indefinitely during the cutting operation, and generally, as a result of these successive ruptures, a poor surface finish is produced on the workpiece.

CONDITION OF WORK MATERIAL

The condition and physical properties of the work material have a direct influence on its machinability. The various conditions and characteristics described as "condition of work material," individually and in combinations, directly influence and determine machinability. Operating conditions, tool material and geometry, and workpiece requirements affect machinability indirectly and can often be used to overcome difficult conditions presented by the work material. On the other hand, they can create situations that increase machining difficulty if they are ignored.

The following eight factors determine the condition of the work material: microstructure, grain size, heat treatment, chemical composition, fabrication, hardness, yield strength and tensile strength.

Microstructure: The microstructure of a metal refers to its grain structure as determined through examination of etched and polished surfaces under a microscope. Metals whose microstructures are similar have similar machining properties. But there can be variations in the microstructure of the same workpiece that will affect machinability.

Grain Size: Grain size and structure of a metal serve as general indicators of its machinability. A metal with small, undistorted grains tends to cut easily and finish easily. Such a metal is ductile, but it is also "gummy." Metals of an intermediate grain size represent a compromise that permits both cutting and finishing machinability. Hardness of a metal must be correlated with grain size and it is generally used as an indicator of machinability.

Heat Treatment: To achieve desired properties metals are typically put through a series of heating and cooling operations when in the solid state. A material may be treated to reduce brittleness, remove stress, to obtain ductility or toughness, to increase strength, to obtain a certain microstructure, to change hardness or to make other changes that affect machinability.

Chemical Composition: Chemical composition of a metal is a major factor in determining its machinability. The effects of their composition however, are not always clear, because the elements that make up an alloy, work both individually and collectively. Certain generalizations about chemical composition of steels in relation to machinability can be made, but nonferrous alloys are too numerous and varied to allow such generalizations.

Controlled addition of elements like sulfur (S), lead (Pb), tellerium (Te), etc . leading to free cutting of soft ductile metals and alloys improve machinability, which will be discussed in detail later in this article.

Fabrication: Whether a metal has been hot rolled, cold rolled, cold drawn, cast, or forged will affect its grain size, ductility, strength, hardness, structure-and therefore-its machinability. The term "wrought" refers to forming of materials into shapes, which are readily altered into components or products using traditional manufacturing techniques. Wrought metals are defined as that group, which are mechanically shaped into, bars, billets, rolls, sheets, plates or tubing. Casting and forging processes result in a near component shape that requires minimal, or in some cases no machining.

Hardness: The textbook definition of hardness is the tendency for a material to resist deformation. Hardness is commonly measured using either the Brinell or Rockwell scales. These tests can be performed with various indenter sizes and loads. The method used to measure hardness involves embedding a specific size and shaped indenter into the surface of the test material, using a predetermined weight. The distance the indenter penetrates the material surface will correspond to a specific hardness value. The greater the indenter surface penetration, the lower the Brinell or Rockwell number, and thus lower the corresponding hardness level. Therefore, higher hardness values on the same scale represent a minimal amount of indenter penetration into the material and thus, by definition, are an indication of an extremely hard part.

These standardized tests provide a consistent method to make comparisons between a variety of workpiece materials or a single material that has undergone various hardening processes.

Yield Strength: Tensile test is used as a means of determining the condition of the material. Yield strength, which can be altered during heat treatment, is measured just prior to the point before permanent deformation takes place. Increased part hardness produces an increase in yield strength.

Tensile Strength: The tensile strength of a material increases along with its yield strength, as it is heat treated to higher hardness levels. Therefore, based on the material selected, a distinct tensile strength level corresponds to certain hardness reading.

Cast Irons

All metals that contain iron (Fe) are known as ferrous materials. Ferrous materials include cast iron, wrought iron, and low carbon and alloy steels. The extensive use of cast iron and steel workpiece materials can be attributed to the fact that iron is one of the most frequently occurring elements in nature. When iron ore and carbon are metallurgically mixed, a wide variety of materials result with a fairly unique set of physical properties. Carbon contents are altered in cast irons and steels to provide changes in hardness, yield and tensile strengths. The physical properties of cast irons and steels can be modified by changing the amount of the iron-carbon mixtures in these materials, as well as their manufacturing process.

Cast iron is an iron-carbon mixture that is generally used to pour sand castings, as opposed to making billets or bar stock. It has excellent flow properties when molten, and therefore is an ideal material for complex cast shapes and intricate molds. This material is often used for automotive engine blocks, cylinder heads, valve bodies, manifolds, heavy equipment oil pans and machine bases.

Gray Cast Iron: Gray cast iron is an extremely versatile, very machinable, relatively low strength cast iron used for pipe, automotive engine blocks, farm implements and fittings. This material receives its dark gray color from the excess carbon in the form of graphite flakes, which also give it its name.

White Cast Iron: White cast iron occurs when all of the carbon in the casting is combined with iron to form cementite (carbides). This is an extremely hard substance that results from the rapid cooling of the casting after it is poured. Since the carbon in this material is transformed into cementite, the resulting color of the material when chipped or fractured is a silvery white. Thus the name white cast iron. However, white cast iron has almost no ductility, and therefore when it is subjected to any type of bending or twisting loads, it fractures. Although the machinability is extremely low, the hard and brittle white cast iron surface is desirable in those instances where a material with extreme abrasion resistance is required. Applications of this material would include plate rolls in a mill, or rock crushers.

Malleable Cast Iron: Malleable iron castings are produced by annealing white iron castings (softened by heating to an elevated temperature for a specific length of time). Malleable iron castings are obtained when hard, brittle cementite in white iron castings is transformed into tempered carbon or graphite in the form of rounded nodules or aggregate during the annealing treatment. The resulting material is a strong, ductile, tough and very machinable product that is used on a broad scope of applications.

Nodular Cast Iron: Nodular or ductile iron is used to manufacture a wide range of automotive engine components including cam shafts, crank shafts, bearing caps and cylinder heads. Nodular iron is strong, ductile, tough and extremely shock resistant. Machinability varies for different grades depending on the matrix structure. In general, ductile iron (such as grade 60-40-18) is easy to machine but produces built-up edges on the cutting tool due to its higher ferrite content. Machining higher strength grades of ductile iron (such as 80-55-06) will result in rapid insert wear due to its pearlitic matrix.

Since every type and grade of cast iron is unique, machining cast iron components depends upon the material's graphite structure, microstructure of the metal matrix, temperature-to-time history of the castings and the distribution of carbon that remains in the metal matrix.

With all of these different variables, machining guidelines are dependent upon the make-up of the material. General "rules of thumb" to follow in regard to cast iron machinability include:

- a reduced carbon content results in a coarser-graphite structure and lower machinability;
- higher silicon content in the iron results in a lower tendency to built-up-edge and better machinability;
- increased pearlitic graphite content makes pearlite or white grades harder and stronger and more demanding on the cutting tool;
- a fine-grained pearlitic matrix is troublesome for machining as the cutting tool needs to work harder and under hotter conditions to cut through the hardest particles.

Steels

Steel materials are comprised mainly of iron and carbon, often with a mixture of alloying elements. The purpose of alloying is either to enhance the material's physical properties or its ultimate manufacturability. The physical property enhancements include improved toughness, tensile strength, hardenability, ductility, and wear resistance. The use of alloying elements can alter the final grain size and structure of a heat-treated steel, which often results in a lower machinability rating of the final product. The biggest difference between cast iron materials and steel is the carbon content. Cast iron materials are compositions of iron and carbon, with a minimum of 1.7 percent carbon to 4.5 percent carbon. Steel has a typical carbon content of .05 percent to 1.5 percent.

Steel's versatility allows the soft steels to be used in drawing applications for automobile fenders, hoods and oil pans, while premium grade high strength steels can be used for cutting tools. Tool selection for machining hardened steel is strongly influenced by specific demands of the components to be produced. The most common difficulties, when machining hardened steel, are the rapid tool wear rate, cracking or chipping of the tool, workpiece dimensional accuracy and surface roughness of the machined surface. Carbide tools can be applied for some operations at low cutting speeds in special cases, whereas ceramic and cubic boron nitrides are the preferred choices.

Plain carbon steels with carbon content below 0.15% are very soft and adhere strongly to the cutting tool. As a result, it is very difficult to achieve good surface finish with such steels due to built-up formation on the cutting edge particularly when the depth of cut is small (as in broaching and gear shaving). In such cases, the selection, proper application, and maintenance of the cutting fluid (coolant) are extremely important.

Machinability of medium carbon steels depends to a large extent on their microstructure. They machine best when they have the coarse pearlite or spheroidized carbide structure. Steels with carbon content in excess of 0.6% machine best in the fully spheroidized condition. As a general rule, tool wear rates increase in a consistent manner as the carbon content of work material is increased beyond 0.35%. Actual machinability of the materials in this group depends on many metallurgical parameters of the particular steel (grain size, heat treatment, cold work, etc.).

In general, surface finish improves with increasing carbon content up to 0.35%, however, the surface finish depends not only on carbon content but also on the cutting operation, the tool geometry and the cutting conditions. When slower cutting processes such as shaping and milling are used, the surface finish is found to be virtually independent on carbon content.

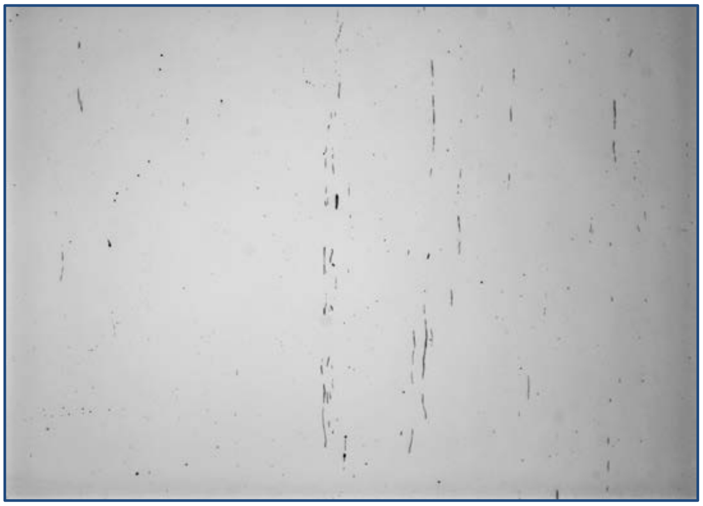
Stainless Steels: As the name implies, this group of materials is designed to resist oxidation and other forms of corrosion, in addition to heat in some instances. These materials have significantly greater corrosion resistance due to the substantial additions of chromium as an alloying element. Stainless steels are used extensively in the food processing, chemical and petroleum industries to transfer corrosive liquids between processing and storage facilities. Stainless steels can be cold formed, forged, machined, welded or extruded. Stainless steels fall into four distinct metallurgical categories with a wide range of machinability ratings. These categories include: austenitic, ferritic, martensitic, and precipitation hardening.

Free Cutting Steels

Machinability rating of plain carbon steels typically peak at a carbon content of 0.18 to 0.22 percent before the machinability starts to decrease because of the higher hardness resulting from higher carbon contents. A steel of optimum machinability-one both soft enough to easily form a chip, yet brittle enough to allow that chip to break and separate-results in longer tool life and a superior surface finish. The 11XX series steels, called resulfurized steels, employ additions of sulfur and manganese to try to create this soft, yet brittle workpiece material.

Sulfur combines with manganese to form a solid but nonmetallic inclusion called manganese sulfide (MnS). Manganese sulfides act as discontinuities in the steel, providing nucleation sites for the chip to break. Manganese is added to tie up the sulfur and prevent it from reacting with the iron in the steel, forming iron sulfides or pyrites that are brittle at steel rolling temperatures.

As shown in the micrograph below, these manganese sulfide inclusions are visible under the microscope, generally elongated, and distributed throughout the steel. An additional benefit provided by these sulfides is their role in the retention of built up edge on the tool, which is influenced by the anti-weld properties of manganese sulfide. Sulfide inclusions promote higher feeds by causing the formation of a broken chip instead of a continuous chip and by providing a built-in lubricant that prevents the chips from sticking to the tool and undermining the cutting edge.



Micrograph showing MnS inclusions in steel

Special leaded steels differ from the normal steels due to the presence of lead (Pb), added approximately in the 0.15-0.35% range, in order to improve their machinability. These steels offer excellent chip removal and are particularly suitable for large production volumes. Addition of lead permits higher speeds as the lubricating action of the dispersed lead particles reduces the friction and, thus, heat. Both mechanisms prolong tool life. For applications requiring no lead, 1215 or a proprietary tin-added 12XX series grade (12T14) maybe appropriate. Although lead does not have any influence on the longitudinal mechanical properties of steels, it reduces their fatigue limit. Furthermore, leaded steels are not suitable for the manufacture of gears, due to their lack of toughness in a transversal direction. It should also be noted that they are not readily weldable resulting in cracking and porosity.

Machinability of Nonferrous Alloys

Aluminum is very easy to machine, although the softer grades tend to form edge build-up resulting in poor surface finish. Thus, high cutting speeds, high rake angles, and high relief angles are recommended. Wrought aluminum alloys with high silicon content and cast aluminum alloys are abrasive; hence, they require harder tool materials. Controlling dimensional tolerances may be a problem in machining of aluminum because it has a high thermal expansion coefficient and a relatively low elastic modulus.

Beryllium is machinable, but because the fine particles produced during machining are toxic, it requires machining in a controlled environment.

Cobalt-based alloys are abrasive and highly work hardening. They require fine, abrasion-resistant tool materials, small feeds, and speeds.

The wrought condition of copper can be difficult to machine because of built-up edge formation, although cast copper alloys are easy to machine. Brasses are easy to machine, in particular with the addition of lead (leaded free-machining brass). The toxicity of lead and associated environmental concerns have to be dealt with however. Bronzes are more difficult to machine than brass.

It is very easy to machine magnesium, with good surface finish and prolonged tool life. However, care needs to be taken because of its high rate of oxidation (pyrophoric) and the danger of fire.

Molybdenum is ductile and but work hardening. To avoid producing poor surface finish sharp tools are essential.

Nickel-based alloys are work hardening, abrasive, and strong at high temperatures. Their machinability depends on their condition and can be improved with annealing.

Tantalum is very work hardening, ductile, and soft. It produces a poor surface finish, and tool wear is high.

Titanium and its alloys have very poor thermal conductivity (the lowest of all metals), causing a significant temperature rise and built-up edge. They are highly reactive and can be difficult to machine.

Tungsten is brittle, strong, and very abrasive; hence, its machinability is low, although it improves significantly at elevated temperatures.

Zirconium has excellent machinability, but requires a coolant-type fluid because of the danger of explosion and fire.